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LOW FREQUENCY INDUCTION HEATING OF LARGE DIAMETER STEEL PREFORMS FOR ROTARY FORGING

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Part I of this report surveys the basic theory of induction heating and heat flow in an inductively heated steel cylinder. Part II describes an induction heating system now in use at the Watervliet Arsenal, and applies the theory of Part I to this system.

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SUBSCRIPTS AND SYMBOLS

Subscripts:

- g - The air gap
- w - The workpiece
- c - The coil

Symbols:

- I - Current (amps)
- R - Resistance (ohms)
- ϕ - The magnetic flux (maxwells)
- H - The magnetic field strength (oersteds)
- B - The flux density (gauss)
- μ_r - The relative permeability, i.e., the permeability of the material divided by the permeability of free space.
- δ - The effective depth of current penetration (cm)
- P - Real power (KW)
- A - The cross sectional area (cm^2)
- P_c - The inside perimeter of the coil (cm)
- E - Voltage (RMS)
- f - Frequency (hertz)
- L - Inductance (henries)
- Z - Impedance (ohms)
- N - Number of turns
- ℓ - The length of the coil (cm)
- $\mathcal{R}$ - Reluctance ($\frac{\text{amps}}{\text{maxwells}}$)
- ρ - Resistivity (ohm-cm)
- T_s - Temperature of surface(°C)
- T_c - Temperature of center (°C)
- P_o - Surface power density ($cal/sec\text{-}cm^2$)
- a - Radius (cm)
- k - Thermal conductivity (cal/sec-cm-°C)
- γ - Density(g/cm^3)
- T_a - Average temperature(°C)
- $\mathbf{c}$ - Specific heat (cal/g°C)

PART I - INDUCTION HEATING

INTRODUCTION:

Induction heating results from a simple and basic phenomenon. Faraday's law states that a changing magnetic field will induce a current in a conductor that is placed in this field. The resistance to the flow of the induced current will result in heating within the conductor. (The power causing the heat is equal to I^2R, where I is the current and R is the resistance.) In order to produce a changing magnetic field, you must first have a changing current within a conductor which will produce the magnetic field. This is accomplished by passing an alternating current through the conductor. If the conductor is formed into a solenoid, the magnetic field becomes concentrated in the center and the result is a practical induction heating coil.

TERMINOLOGY:

Magnetic flux, Ø, as used herein, refers to the lines of force that run between the poles of a magnet. They are abstractions used to help visualize what takes place in a magnetic field. A magnetic field is the area around a magnet where the flux lines exist.

The permeability is a property of the material and is often given as its value relative to the permeability of free space, μ_o = $.4\pi \frac{\text{maxwell}}{\text{amp - cm}}$. μ/μ_o represents the relative permeability (μ_r) of a material. The reluctance, $\mathcal{R}$, is a term used in magnetic circuits, analogous to the resistance in electrical circuits. Thus, its value is an indication of the resistance to the magnetic flux within a material.

Reference depth, δ, or effective depth of current penetration, in a large diameter workpiece, refers to the depth to which the current exists within the workpiece. Alternating current actually exists throughout the cross section of a conductor. However, since its density decreases the greater the distance from the surface, for all practical purposes the current may be assumed to exist only from the surface to the reference depth. A large diameter workpiece means one in which the wall thickness is at least 1.5 times greater than the reference depth. The words, "workpiece" and "preform", are used interchangeably in this report.

Real power refers to the power developed as a result of the current that is in phase with the voltage. Reactive power is the product of the voltage and the current that is 90 degrees out of phase with the voltage (see Figure 1). The power factor is the cosine of the angle between the voltage and current.

THE COIL FLUX:

The magnetic flux produced by the coil, or solenoid, is composed of three parts: the flux in the air gap (the space between the coil and workpiece), the flux in the workpiece, and the flux in the coil (see Figure 2). From the equation $B = \mu H$, with $\mu = 1$ for the air gap,

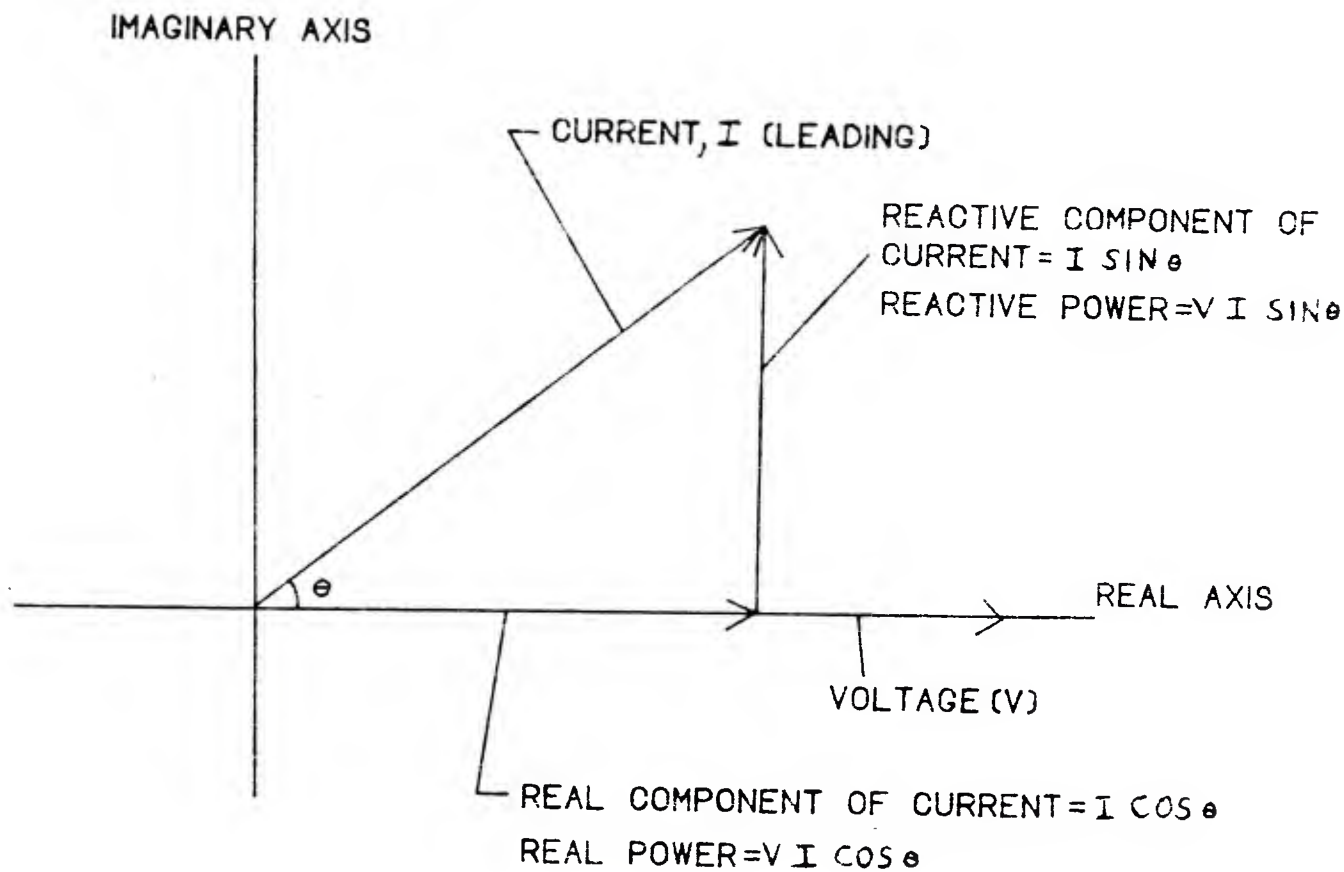
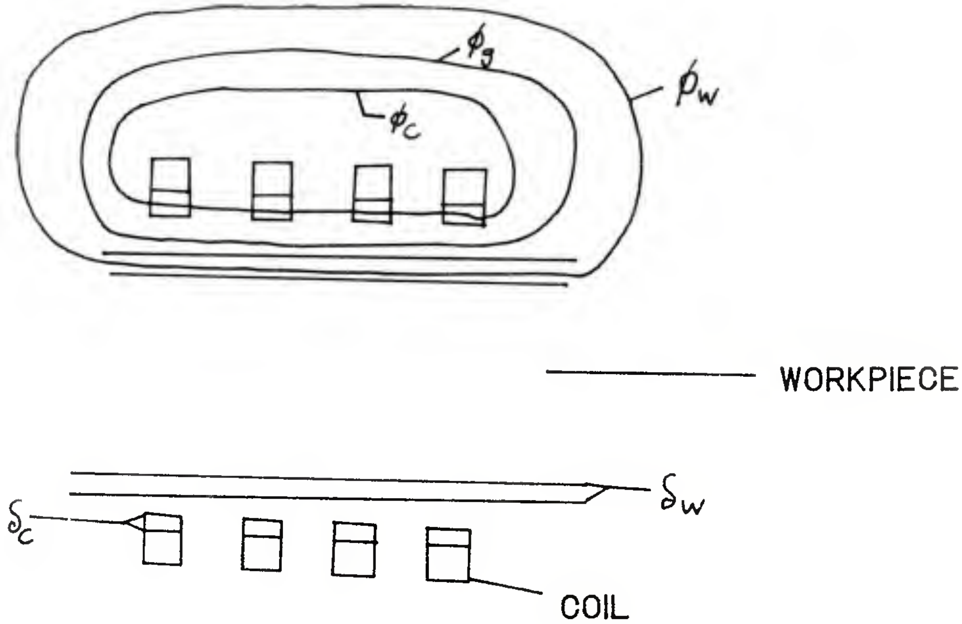
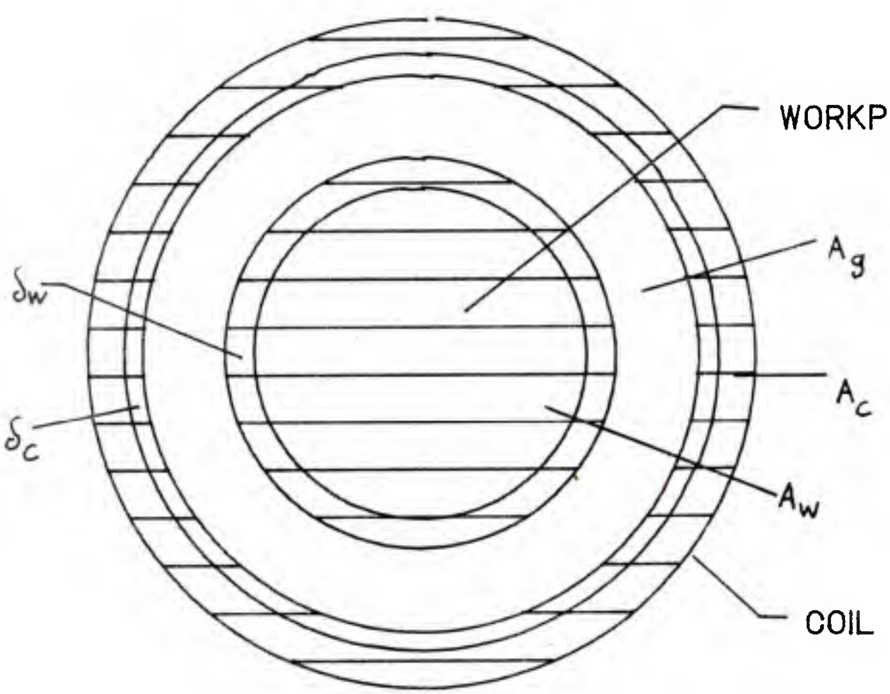


Figure 1. Power Factor



A-SIDE VIEW



B-END VIEW

Figure 2. Flux Flow

it follows that:

$$B_g = \frac{\emptyset_g}{A_g} = H, \text{ or } \emptyset_g = HA_g \qquad (1)$$

The flux in the workpiece lags the magnetic field intensity by a greater amount as the penetration becomes deeper. Consequently, the flux must be represented by a phasor (complex number):

$$B_W = \frac{\emptyset_W}{A_W} = \mu_W H(P-jQ), \text{ or, } \emptyset_W = \mu_W A_W H(P-jQ)^{[1]} \qquad (2)$$

where P and Q are factors introduced to account for the shift in phase of the flux.

The flux within the coil (a cylindrical shape is not assumed), which is made from copper, is:

$$B_c = \frac{\emptyset_c}{A_c} = \frac{\emptyset_c}{P_c\delta_c} = H(1-j), \text{ or, } \emptyset_c = \frac{K_r P_c \delta_c}{2} H(1-j)^{[1]} \qquad (3)$$

where K_r is a factor introduced to account for spacing between turns, and other imperfections, and (1-J) accounts for the phase shift within the copper of the coil. The area terms, $\frac{P_c\delta_c}{2}$, result from assuming an infinite radius of curvature, so that the area is viewed as a rectangle with sides equal to P_c and $\frac{\delta_c}{2}$. $\frac{\delta_c}{2}$ is used because the flux in the copper cannot increase after the depth of penetration exceeds one-half the copper thickness, and it is assumed the penetration is equal to the copper thickness.

The total flux can thus be given as:

$$\emptyset_T = HA_g + \mu_W HA_W(P-jQ) + \frac{K_r P_c \delta_c H(1-j)}{2} \qquad (4)$$

ELECTRICAL PARAMETERS:

Since $E = L\frac{di}{dt}$ and $E = N\frac{d\emptyset}{dt}$, then $N\frac{d\emptyset}{dt} = L\frac{di}{dt}$.[2]

Integrating both sides yields $N\int\frac{d\emptyset}{dt}\,dt = L\int\frac{di}{dt}$ or $N\emptyset = LI$ plus a constant which is assumed zero.

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1. Reference is listed at end of report
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Since $E = ZI = (j2\pi fL)\, I$ (neglecting coil resistance) then

$L \dfrac{E}{j2\pi fL} = N\emptyset$ or $E = j2\pi fN\emptyset$. If the root-mean-square (RMS) value of the voltage is used ($E = E_{RMS}\sqrt{2}$ for a sinusoid) and the flux is given in maxwells, the equation for the coil voltage becomes

$$E = j\sqrt{2}\ \pi f N_c \emptyset_T\ 10^{-8} \qquad (5)$$

Ampere's law states that $\oint \vec{B}\cdot d\vec{\ell} = \mu_o I$.[3] If this equation is applied to a solenoid, the result is $B = \mu_o\, I \dfrac{N}{\ell}$ or, since $B = \mu H$, $I = \dfrac{\mu}{\mu o} H \dfrac{\ell}{N}$.

The relative permeability, $\dfrac{\mu}{\mu o}$, in this case is one, and if H is given in oersteds, ℓ in centimeters, and the RMS current is used, the equation becomes $I_c = \dfrac{H\ell c}{.4\pi N_c\sqrt{2}}$ (6)

If a short coil is being considered a term can be added to account for the mmf (magnetomotive force, NI) required to overcome the reluctance outside the coil due to end effect. The equation then becomes

$$I_c = \frac{1}{.4\pi N_c\sqrt{2}} \left(H\ell_c + \Re\, \emptyset_T\right) \text{[4]} \quad (7)$$

where the term, $\dfrac{\Re\emptyset_T}{.4\pi N_c\sqrt{2}}$, has been added to equation 6. According to Baker[1], $\Re = \dfrac{1.8}{P_c}$ for a solenoid.

If equation 4 is substituted into equation 5 for the value of $\emptyset$ the result is

$$E_c = \sqrt{2}\pi f N_c H\ 10^{-8} \left[\left(\mu_w A_w Q + \frac{K_r P_c \delta_c}{2}\right) + j \left(A_g + \mu_w A_w P + \frac{K_r P_c \delta c}{2}\right) \right] \quad (8)$$

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If equation 8 is multiplied by equation 6, this gives

$$E_c I_c = 2.5fH^2 \ell_c \, 10^{-8} \left[\left(\mu A_w Q + \frac{K_r P_c \delta_c}{2} \right) + j \left(A_g + \mu A_w P + \frac{K_r P_c \delta_c}{2} \right) \right] \qquad (9)$$

Equation 9 gives the complex volt-amperes of the coil where the real term is the power input to the coil, which is made up of the power developed in the workpiece plus the power lost in the coil copper. If the part of the term representing the power in the workpiece is extracted, the result is:

$$P_W = 2.5fH^2 \ell_c \, 10^{-8} \, (\mu A_w Q) \qquad (10)$$

Thus, if you have values for P and Q (see Fig. 3 for a large diameter workpiece) and you know the amount of power you want to develop in the workpiece, then from Equation 10, you can calculate H, the magnetic field strength. If this value of H is substituted into Equation 4, the total flux ($\emptyset_T$) can be found. And finally, if the value of $\emptyset_T$ is substituted into Equation 5, along with the coil voltage, it is possible to calculate the number of turns, N_c, you will need in order to obtain the power desired in the workpiece. If the values of H and N are substituted into Equation 6, the current in the coil can be found. Other values can also be found from the preceding equations such as coil power factor, coil efficiency, etc.

EFFICIENCY:

The current flowing in an induction coil is usually quite high, so that some means of cooling is required. This can usually be done by using a hollow copper coil and circulating water through the coil.

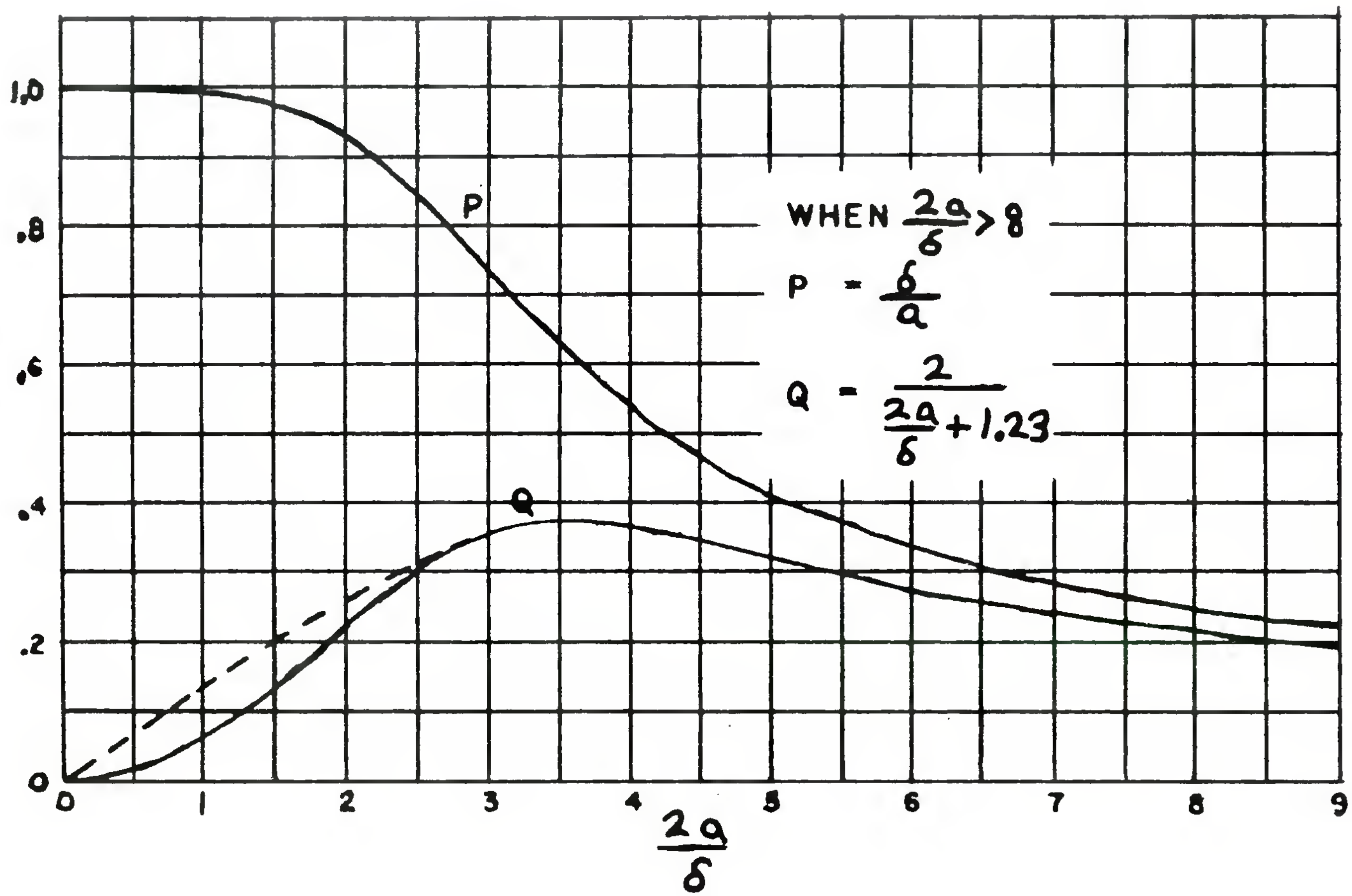

Figure 3. P and Q Factors

By keeping the coil at or near room temperature, burning of the insulation is prevented. Since the resistivity of copper increases with temperature, the resistance of the coil can be kept at a minimum. Otherwise, with increased resistance of the coil, the efficiency would decrease.

The efficiency of the coil is the power developed in the workpiece divided by the power input to the coil. In order to calculate this, you must know the resistance of the coil. The resistance is, for a single turn coil:

$R = \frac{\rho p_c}{\ell \delta_c}$, where the length times the effective depth of current penetration gives the area and the perimeter gives the length of current travel. If the single turn is divided into N turns, with the length (ℓ) the same, the result is:

$$R_c = \frac{\rho (Npc)}{\frac{\ell}{N}\delta_c} = \frac{\rho p_c N^2}{\ell \delta c} \qquad (11)$$

REFERENCE DEPTH:

The current that is induced in the workpiece, called Eddy Current, decreases in magnitude the deeper the penetration. It has been found that this current can be considered to flow in a band near the surface of the workpiece and that no Eddy Current exists deeper than this depth. The equation for effective depth of current penetration, or reference depth, is:

$$\delta = 5040 \sqrt{\frac{\rho}{\mu_r f}} \text{ cm.} \text{[5]} \qquad (12)$$

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5. Reference is listed at end of report.

The greater the resistivity, the greater the reference depth. The resistivity increases with increasing temperature for most conductors. Assuming constant permeability and frequency, the efficiency will increase as the workpiece is inductively heated, due to an increase of workpiece resistance. But the permeability does change with magnetic field strength and with temperature. For steel, the relationship between μ_r and H is given by Baker[1] as: (For H greater than 60 oersteds)

$$\mu_r = \frac{32,400}{H} + 1 \qquad (13)$$

Steel changes to a relative permeability of one at the Curie temperature (about 1400°F for steel) and remains at one for all temperatures above Curie, i.e., it becomes non-magnetic above the Curie temperature. Thus, there is a dramatic increase in reference depth when the Curie temperature is reached and, therefore, a large decrease in workpiece resistance. This results in a large decrease in coil efficiency when the Curie temperature is reached. It can also be seen that this dramatic change in μ affects the value of H in equation 10 and thus the value of $\emptyset$ in Equation 4. This, in turn, affects the relationship between the voltage and flux in Equation 5. Therefore, calculations of coil turns being done for heating steel must be done for temperatures above and below Curie if it is expected to heat above 1400°F.

POWER FACTOR:

The power factor of an induction coil is generally less than .5 lagging. To avoid excessive current draw from the voltage source,

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power factor correcting capacitors are connected in parallel with the coil. From Equation 9 the imaginary part gives the reactive power consumed by the coil or, in turn, the volt-amp reactive (VARS) of capacitors required to correct the power factor to one.

Dividing Equation 8, the voltage, by Equation 6, the current, gives the impedance of the coil. The imaginary part is the total inductive reactance of the coil.

$$X_L = \frac{8\pi^2 f N^2 10^{-9}}{\ell}\left(A_g + \mu A_w P + \frac{K_r p_c \delta_c}{2}\right)$$

Since $X_L = 2\pi f L$, the inductance of the coil may be found and used in equation $C = \frac{1}{(2\pi f)^2 L}$ to find the capacitance (C, in farads) required to make the power factor equal to one.

THE HEATING CYCLE:

Heating by induction involves heating near the surface of the workpiece and having heat conducted toward the center. Basically, two things are of concern, viz., (1) How much energy is required to raise the workpiece to the temperature desired and (2) What will the temperature distribution be at the end of heating.

Values are available that give the energy per pound required to raise a given material to a given temperature. Thus, the energy required to heat the workpiece can be found. In induction heating, energy is usually given in kilowatt hours (KWH). If the power is known, the heat time can be found from the relationship:

$$\text{Time} = \frac{KWH}{KW} \qquad (14)$$

Consideration must also be given to radiation loss from the workpiece and possibly to power line loss from the source to the coil. Also, the efficiency of the coil must be considered. The KW in Equation 14 would then be:

$$KW = \left(\left[KW\ (\text{Source}) - KW\ (\text{line loss}) \right] \times \text{efficiency} \right) - KW\ (\text{radiation loss})$$

The temperature difference between surface and center of the workpiece is of greatest concern when heating by induction. Assuming a constant power input, it has been shown that the following relationship exists:

$$T_s - T_c = \frac{P_o a}{2k} K_1 \quad K_2 \ [6] \qquad (15)$$

K_1 (see Fig. 4) corrects for the fact that the heat is generated to a certain depth below the surface with induction heating, and K_2 is a term that corrects for a two power level heating cycle. It is theoretically possible[6] to reduce total heat time by using two power levels, with $P_1 > P_2$. If P_1 is the first power level for time, t_a, and P_2 is the second power level for time, t_b, then, K_2 may be found from the equation:

$$K_2 = \frac{1 + \frac{t_b}{t_a}}{\frac{P_1}{P_2} + \frac{t_b}{t_a}} \ [6] \qquad (15a)$$

Equation 15a applies only if the temperature difference between surface and center reaches equilibrium after each power level is used. This time is given by the equation:

$$t = \frac{\gamma c a^2}{4k} \ [6]$$

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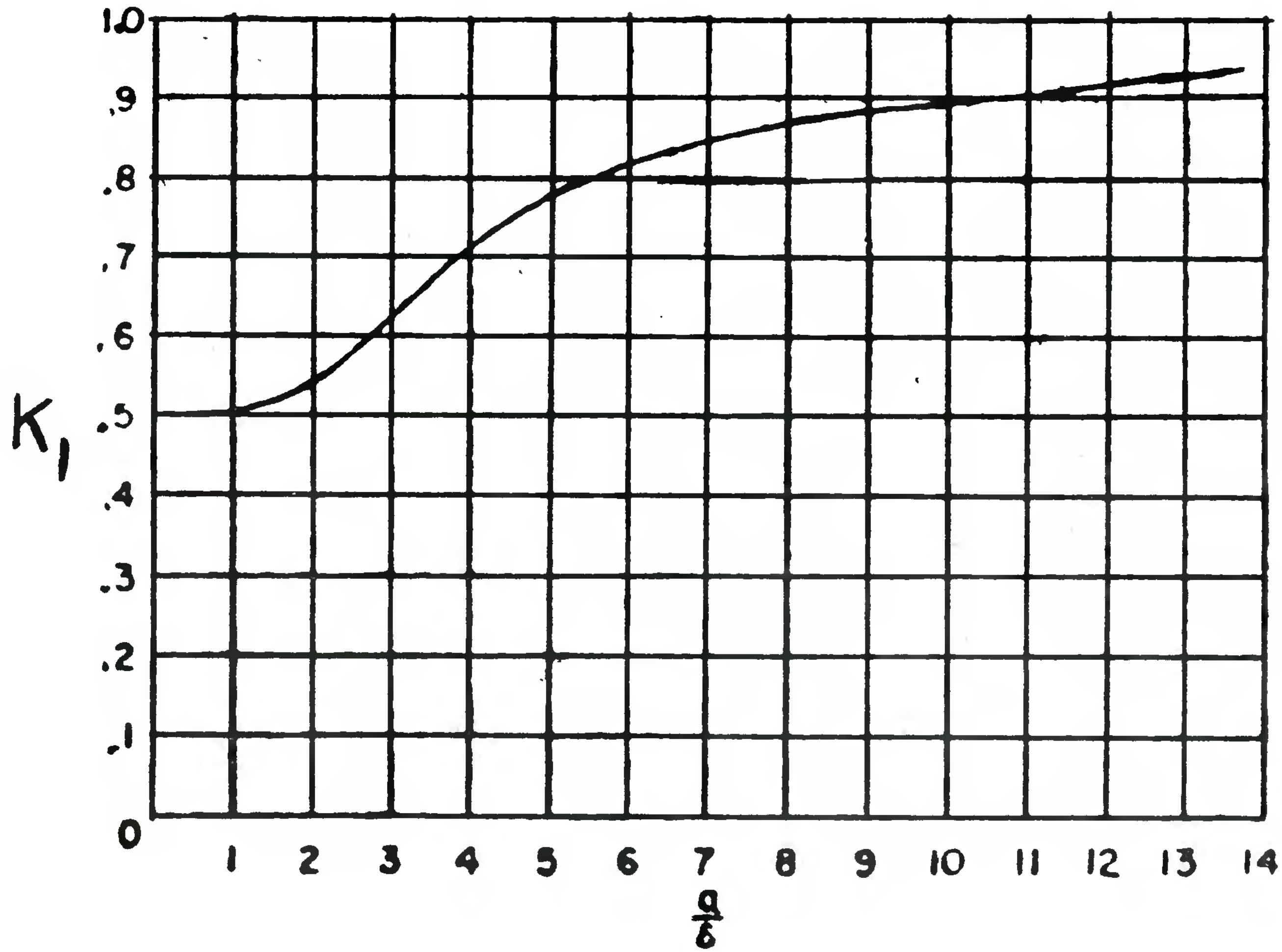

Figure 4. Depth Correction Factor

If the time to heat, from Equation 14, is used, P_0 may be found from the equation:

$$P_0 = \frac{\gamma c a T_a}{2t_1} \quad [6] \qquad (16)$$

where, t_1 is the time to heat the workpiece.

When power is turned off at the coil, the temperature difference between surface and center begins to decrease. In a time, t_2, the difference in temperature has dropped to 10% of its initial value, where:

$$t_2 = \frac{.154\gamma c a^2}{k} \text{ seconds} \quad [6] \qquad (17)$$

The time, t_2, is important because it allows for calculation of temperature difference, when time is involved in moving the workpiece from the coil to its final destination.

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6. Reference is listed at end of report

PART II - THE CHESTON SYSTEM

GENERAL DESCRIPTION:

This induction system was designed and built by the Cheston Company of Rancocas, New Jersey, now called IPE-Cheston of Madison Heights, Michigan. The system consists of four induction heating lines, plus associated apparatus. Each line is capable of heating approximately 2.2 tons per hour to a temperature of 1900°F. The basic system covers an area of about 1300 square feet, not including the area covered by the transfer trolley tracks and the outside cooling tower. There are two levels. The lower level has four induction coil lines running parallel to one another (see Figure 5). The induction coils are located in the center of each line. The coil line, on each side of the coil, consists of steel plate with fiberglass insulation on the inside and removable top covers. Each line has 11 rollers used to oscillate the preform back and forth through the induction coil at a speed of about 2 inches per second. Also, on the lower level, are the closed circuit cooling system and the transfer trolley. The upper level contains the electrical equipment and control circuits. This includes the main supply transformers, tripling transformers, capacitors, reactors, control boards, relays, meters and temperature readouts.

Preforms are loaded by overhead cranes onto a 48 foot long roller system. A transfer trolley (Figure 6) then transfers the preform from the loading rollers to any of the four coil lines. Preform length is limited to 180 inches by the size of the trolley and coil lines.

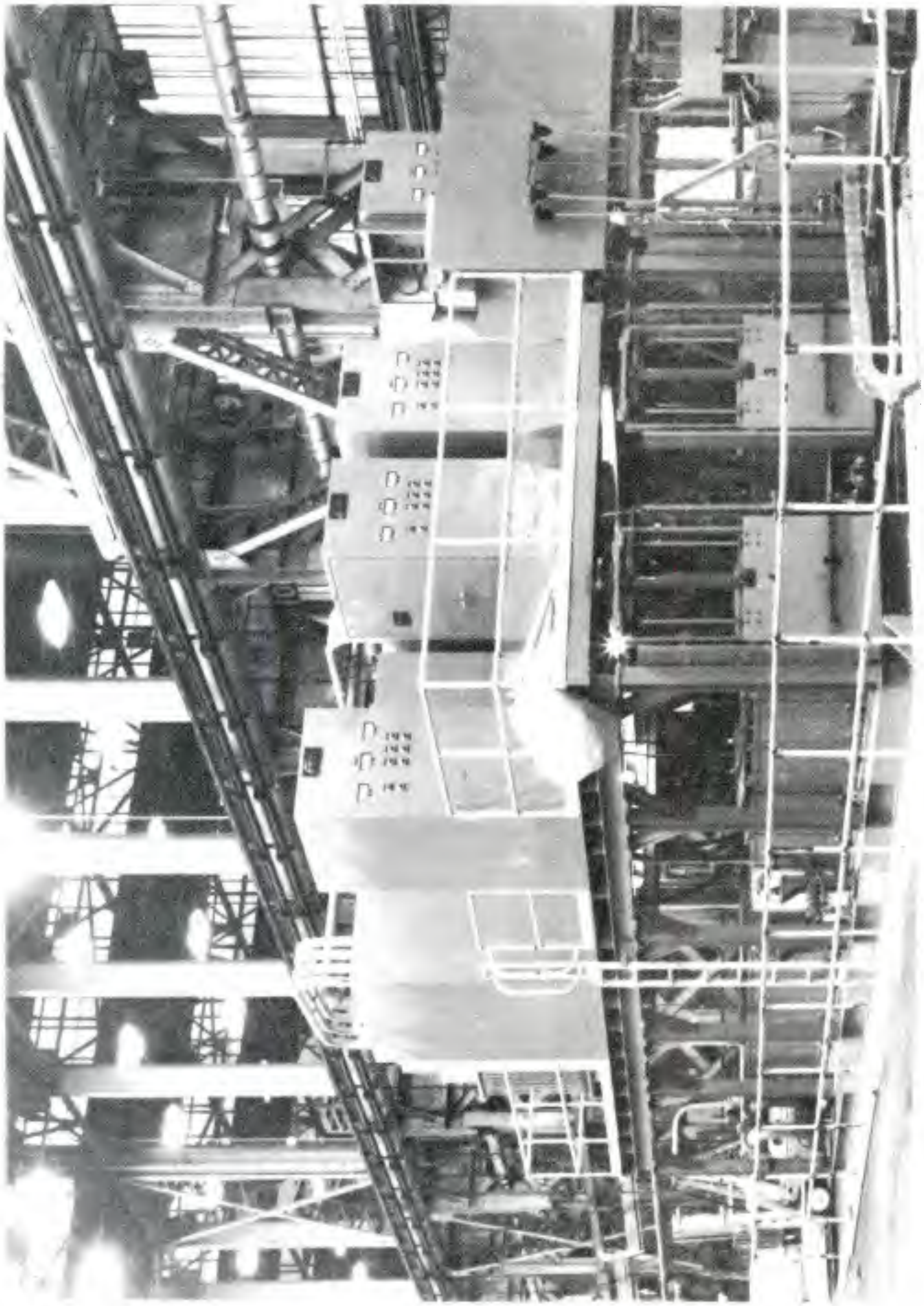

Figure 5. Cheston Induction Heating System

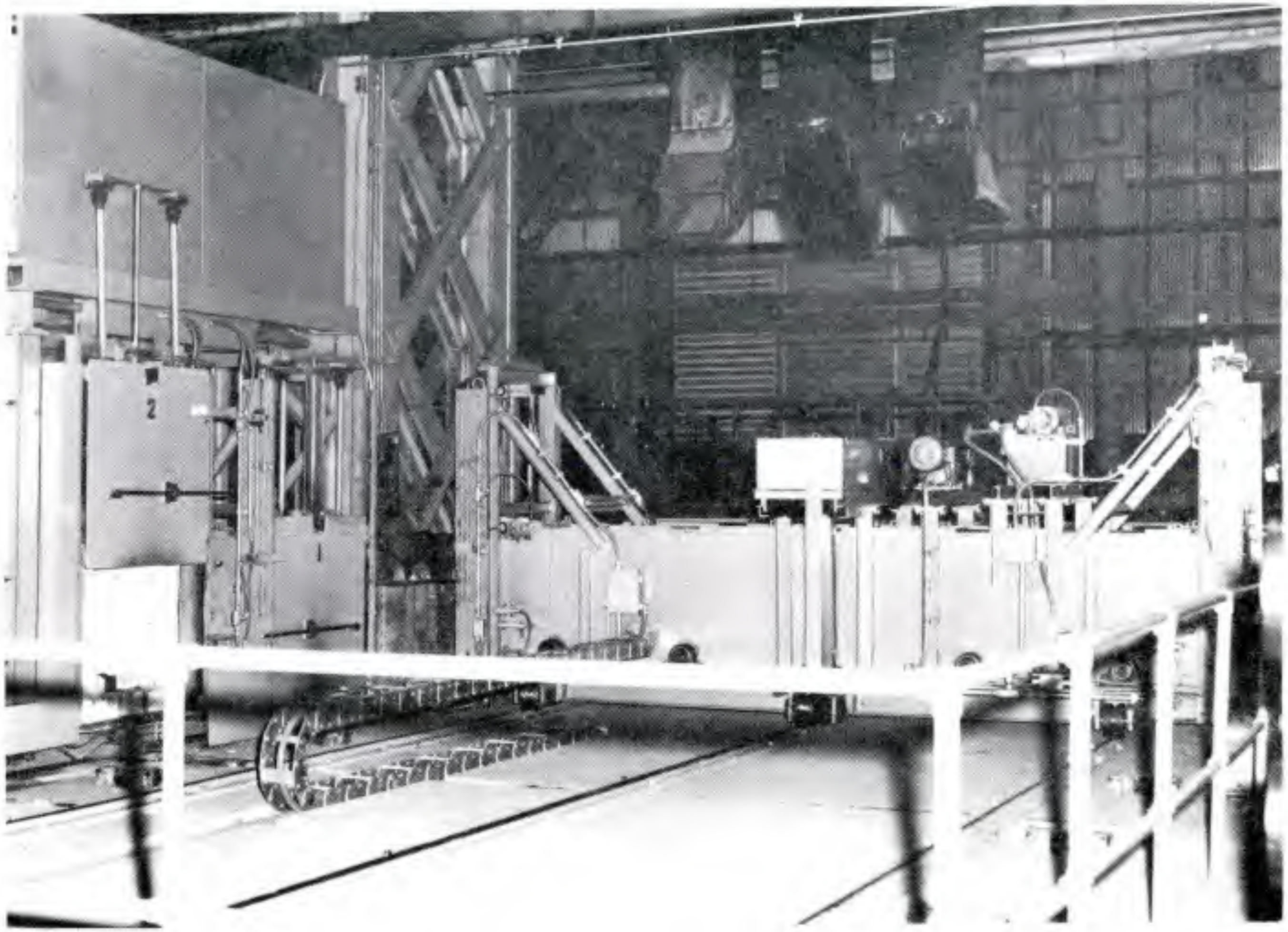

Figure 6. Transfer Trolley

Preforms are unloaded by the same transfer trolley to a series of rollers that move the preform to the rotary forge.

There are presently four sizes of induction coils used on the system. They are as follows:

Inside Diameter (in)	No. Turns	Preform Diameter (in)
27	19	20
22	22	17.5
19	26	15
17	29	13

All the coils are 21 inches long and use hollow rectangular copper tubing; they are water cooled by passing water through the copper inside diameter. Studs, brazed to the coil turns and fastened to a fiber board, are used to contain the coil. One compression type, 17 inch diameter coil, has been purchased to test the possibility of increased coil life over the stud type construction. The 19 inch diameter coil will also be the compression type. All the coils have a cast refractory liner inside the coil and the stud type construction uses cast refractory end plates. The compression coils use a transite board and a water cooled stainless steel plate on the ends.

The heating cycle begins with one end of the preform half way into the coil and continues until the other end is half way into the coil. The direction is then reversed and the preform again travels until the end is half way into the coil. This constitutes one count as recorded by a counter on the control panel. The preform will oscillate, with power to the coil, for the number of counts set on the counter.

The surface temperature of the workpiece is measured, as it is heating, by an infrared type temperature instrument. Each coil line has two instruments located on each end of the induction coil. Temperature readout occurs in digital form on the control panel, with the readout range limited to 1500°F - 2500°F. As the workpiece exits the transfer trolley, another infrared type instrument measures the surface temperature. This readout is automatically recorded on paper to give a final surface temperature before the workpiece reaches the forge.

ELECTRICAL DESCRIPTION:

Electric power is fed from a 13,200 VAC, three phase, 60 hertz line. The voltage is brought down to 480 VAC, three phase, 60 hertz by two 2000 KVA transformers. The three phase 60 hertz is then converted to 180 hertz, single phase, by three tripling transformers, which are toroidally wound with high permeability steel cores used to accentuate the third harmonic component of current; the third harmonic of 60 hertz being 180 hertz. The tripling transformer circuit is as shown in Figure 7. The capacitors are used to correct the power factor. Figure 8 shows how by connecting the output of the three tripling transformers in series, the fundamental component cancels and, since the third harmonics are all in phase, they add together.

The output of the tripling transformers then connects to the induction coil. In parallel are capacitors and two saturable core

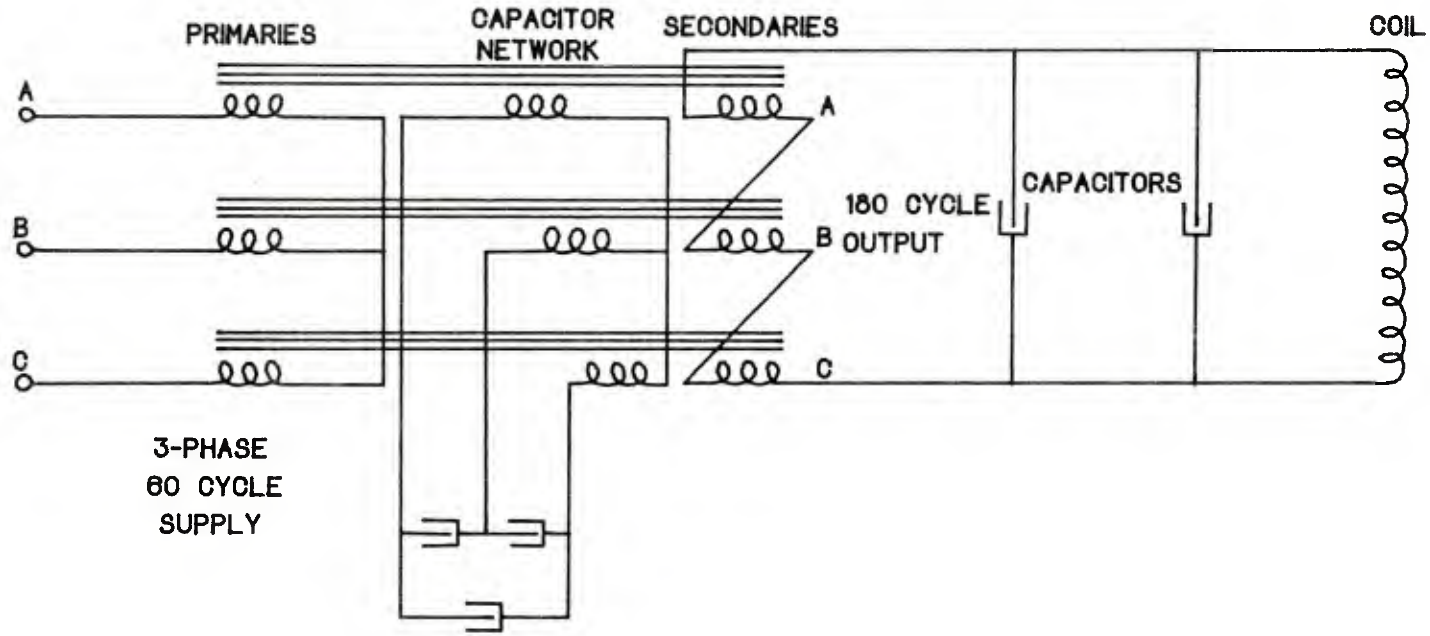

Figure 7. Tripling Transformers

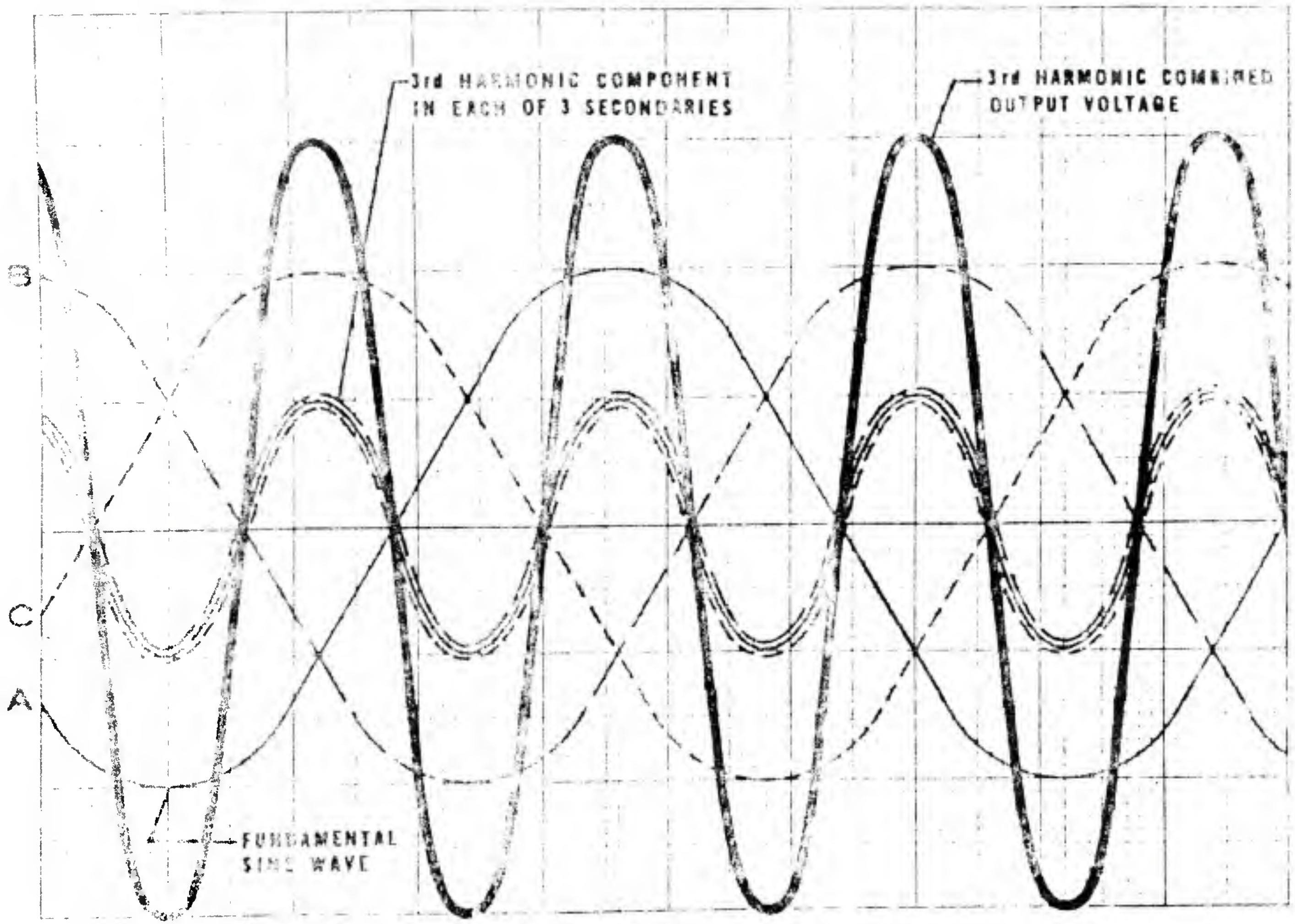

Figure 8. Third Harmonic Voltage

reactors, with a variable inductance, used to control coil voltage.

COOLING SYSTEM:

The cooling system consists of two parts. The closed system circulates purified water that is pumped from an 800 gallon storage tank through some of the electrical components, including the tripling transformers, the capacitors, silicon control rectifiers, reactors and bus bar and then, back to the tank. The tank is provided with a sand filter that draws water from the tank, through the sand, and back to the tank. Water is added, as the need arises, to the tank through a deionization tank that purifies the water.

The open system pumps water from a 2000 gallon storage tank, through a heat exchanger coupled to the closed circuit system, then, through parallel connections to the coil turns and coil line rollers and back through a cooling tower to the tank. The cooling tower has two thermostatically controlled fans that operate when the tank water temperature exceeds 80°F. The open system uses city water and is provided with a conductivity sensor that dumps the water in the tank when the conductivity of the water exceeds a pre-set value. Fresh city water is added automatically as the water empties, until the conductivity is below the set value. The tank water is constantly pumped through the sand filter and returned to the tank.

POWER CONTROL:

Enough capacitors are used to provide a leading power factor in combination with the heating coil and reactors. The more leading the power factor, the greater will be the voltage across the coil. This is illustrated vectorially in Figure 9. The diagram shows the secondary

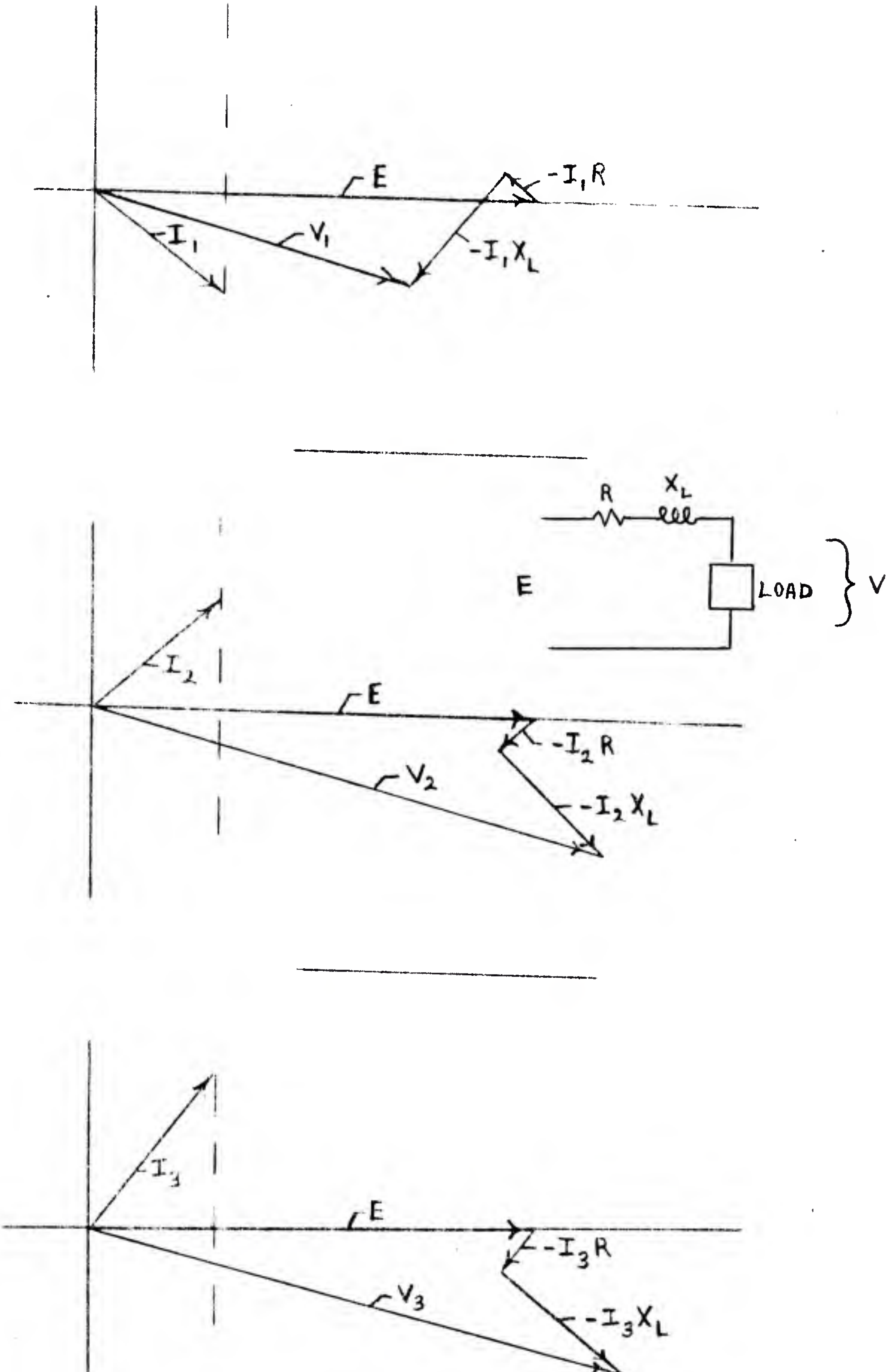

Figure 9. Voltage Control

voltage, E, of a transformer, analogous to the output of the tripling transformers. R and X_L represent the resistance and inductive reactance of the transformers, and the load represents the impedance from the combination of the heating coil, capacitors and reactors. With E assumed constant as the reference phasor, the load is first assumed to have a lagging power factor. V_1, the voltage across the induction heating coil is then given as:

$$V_1 = E - I_1 (R+jX_L)$$

For I_2, a leading power factor is shown, and the corresponding increase in V_2 can be seen. For I_3, a more leading current results in a still greater value of V_3.

The increase in voltage across the coil, of course, results in an increase in power to the load. The reactors are arranged in such a way that increasing the inductance of the reactor will increase the overall inductance of the circuit. To raise the reactor inductance, the permeability of the reactor core must be raised, since $L \sim \mu$. This means that the magnetic field strength (H) must be lowered, since $\mu \sim \frac{1}{H}$ as the reactor core becomes saturated. The reactor, in addition to being connected in parallel to the heating coil, is connected to a D.C. voltage supply. Thus, if the D.C. voltage to the reactor is decreased, H will be decreased, μ will increase and L will increase. Similarly, if the D.C. voltage to the reactor is increased, μ will decrease, L will decrease and the power factor of the circuit will be less leading, resulting in less voltage across the coil. Therefore, by varying the

D.C. voltage to the reactor, it is possible to vary the voltage and, thus, the power to the heating coil.

The D.C. voltage to the reactor is supplied through two silicon control rectifiers (SCR's) from a center tapped transformer as shown in Figure 10. The transformer is supplied from one phase of the 480V 60 hertz, three phase transformer secondary. Gate voltage for the SCR's comes from the electronic control circuits.

ELECTRONIC CONTROL CIRCUITS:

The control circuit is made up of four printed circuit boards: (1) the comparator board,(2) relay or current control board,(3) firing board and(4) hard firing board.

Each coil line has a potentiometer for setting the coil voltage limit and a potentiometer for the power level to the coil. There is a coil voltage meter (red-lined at 800V), a current meter (red-lined at 1400A) giving the current drawn from one phase of the 480V, three phase, supply transformer and a coil power meter (red-lined at 900KW), along with a transducer that senses coil power and outputs it as a 0-1 VDC signal that is sent to the comparator board. Other signals sent to the comparator board are the coil voltage, as a 0-100 VAC signal, the power level, as a 0-5 VDC signal, and the voltage limit setting as a 0-5 VDC signal (see Figure 11). The power level setting, and power signal feed into a differential amplifier. The voltage signal is rectified and fed to another differential amplifier along with the voltage limit signal. The outputs of the two differential amplifiers feed to an integrating amplifier, and the output of the integrating amplifier feeds to an

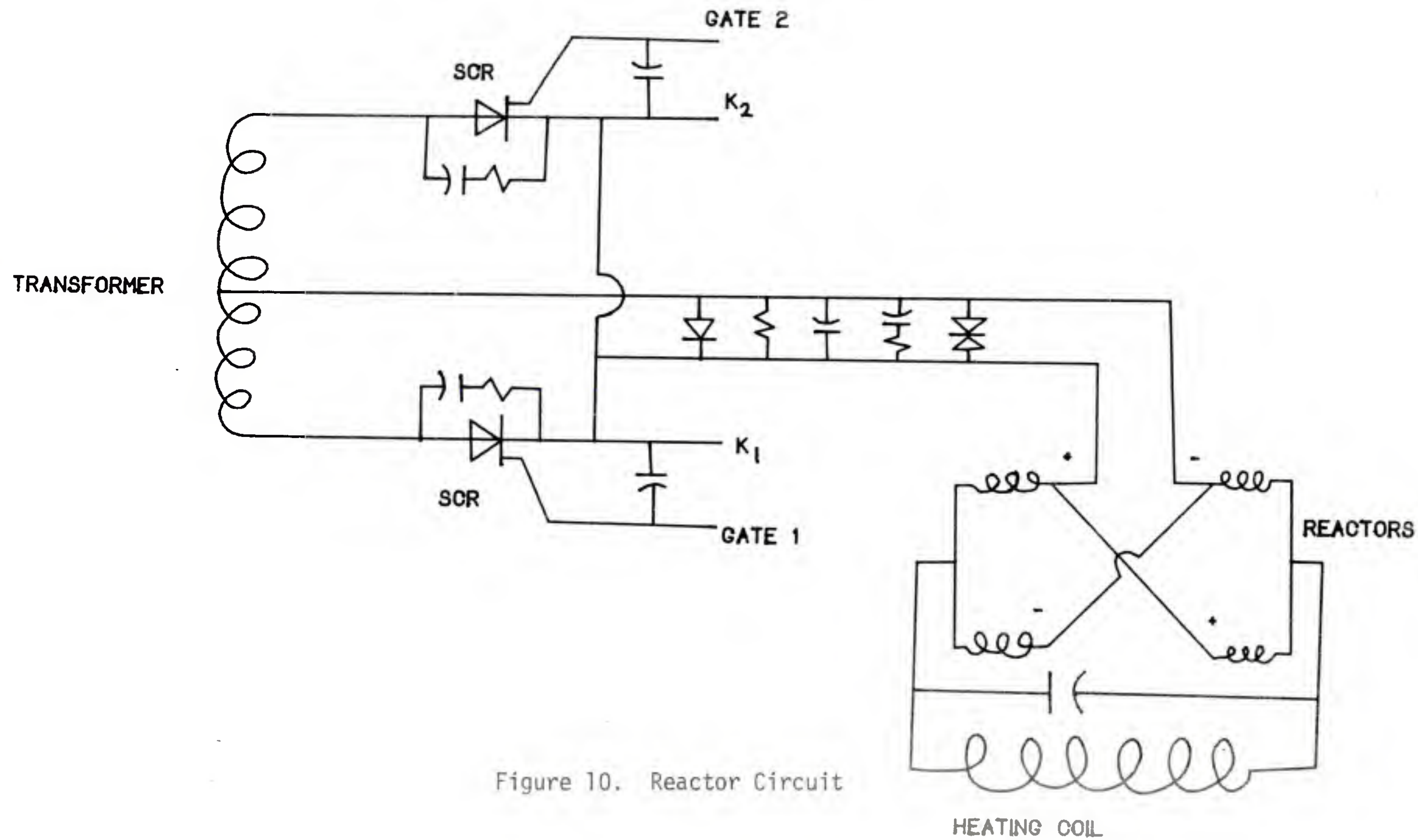

Figure 10. Reactor Circuit

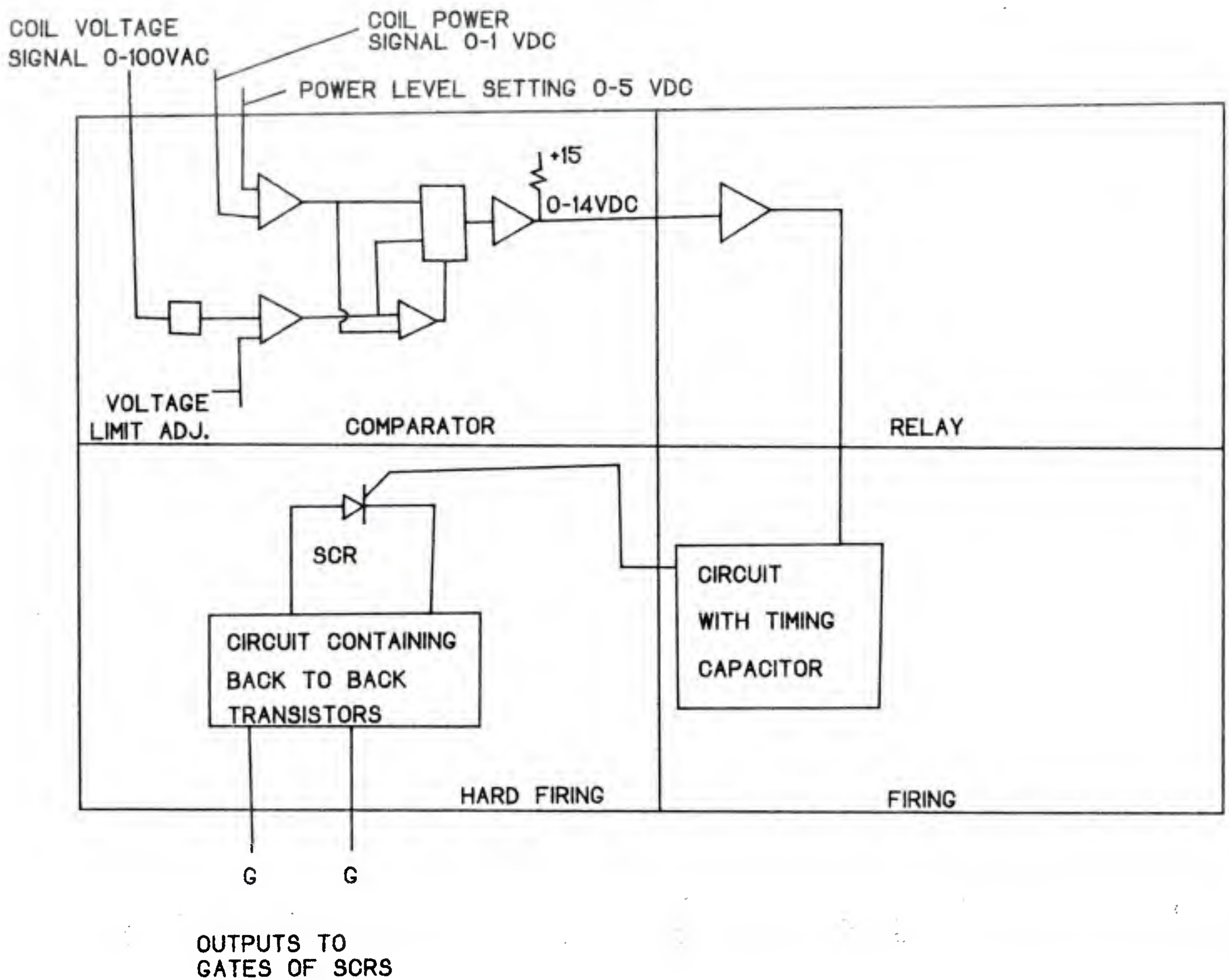

Figure 11. Electronic Control Circuits

electronic switch that is composed of a NAND gate along with a double pole switch. There is also a +5 volt signal into the NAND gate. The outputs from the two differential amplifiers also feed to the two contacts on the electronic switch. Depending on whether the electronic switch is on or off, either the output from the differential amplifier receiving the power signals, or from the differential amplifier receiving the voltage signal, is sent to an operational amplifier.

If the voltage from the induction coil is below the voltage limit signal, the output of the integrating amplifier will cause the electronic switch to disconnect the output from the operational amplifier receiving the voltage signals and connect the output from the power differential amplifier to the operational amplifier. The system is now in power control and will automatically adjust coil voltage to maintain the power to the coil at the setting of the power control potentiometer.

If the coil voltage should reach the voltage limit setting, the output from the integrating amplifier will cause the electronic switch to disconnect the output from the power differential amplifier and connect the output from the voltage differential amplifier to the operational amplifier. The system is now in voltage control, and will automatically prevent the coil voltage from exceeding the voltage limit setting.

The output from the operational amplifier will be a negative voltage that combines with a +15 volt signal to produce a variable voltage signal between 0-14VDC that outputs from the comparator board. This signal is further amplified by the relay board and is input to the firing board. The signal goes to the base of a transistor, thus varying the bias voltage as the 0-14VDC signal varies. The varying bias voltage controls the transistor emitter to collector current which, in turn, varies the charging rate of a capacitor. The capacitor is connected between the emitter and base one of a unijunction transistor. When the voltage across the capacitor reaches a certain value, it causes the unijunction transistor to conduct. The primary of a transformer is connected to the unijunction transistor so that when it conducts it produces a pulse in the secondary of the transformer. This pulse goes to the gate of an SCR on the hard firing board.

The hard firing board contains two transistors, one connected to the gate of one SCR in the reactor rectifying circuit, and the other transistor connected to the gate of the other SCR. When the pulse causes the SCR on the hard firing board to turn on, bias is applied to one of the transistors. This provides voltage to the gate of whichever SCR has positive voltage on the anode, since the transformer supplying voltage to bias the transistor is in phase with the voltage to the reactor rectifier SCR's.

Thus, the voltage from the comparator board varies the charging time for the capacitor in the firing board which, in turn, controls when the transistor will supply gate voltage to the reactor rectifier SCR's. Any variation in the voltage signal from the comparator board will vary the reactor current and thus the induction coil voltage, so that, through feedback, the reactor current is constantly varying to maintain coil power or to limit coil voltage.

THE COIL:

The 17 inch coil (presently used on the system for heating a 13 inch outside diameter, 4.5 inch inside diameter and 90 inch long preform) has 29 turns. To show how the equation given in Part I may be used to verify mathematically that 29 turns are, indeed, the number required, a sample calculation will be given. First, equation 10 must be solved for H. The power, P_W, in this equation is equal to the power at the coil, times the efficiency of the coil. Estimating an efficiency of 75 percent above Curie temperature and allowing 12 KW power loss in the power lines, the power developed at the coil is 900 - 12 = 888 KW. Multiplying by the efficiency, the result is (888 KW) x (.75) = 666 KW. The frequency is 180 hertz, the length of the coil is 53.53 cm and the area of the workpiece is 754 cm^2. μ_r is equal to one, above Curie, and Q is equal to .2138 (see Figure 3). The equation then is:

$$666{,}000 = 2.5(180)\, H^2(53.53)\, 10^{-8}(754)\, (.2138)$$

and H is equal to 4141 oersteds.

Next, equation 4 can be applied to find the total flux, ϕ_T. Values not already given are:

$A_g = 608\ cm^2$

$P = .2462$

$K_r = .8$

$P_c = 136$ cm

$\delta_c = .493$ cm

The equation then is:

$$\emptyset_T = 4141 \left[\left((608) + (754)(.2462) + \frac{.8(136)(.493)}{2} \right) - j \left((754)(.2138) + \frac{.8(136)(.493)}{2} \right) \right]$$

and $\emptyset_T$ is equal to 3397500 - j778609. The magnitude then is 3,485,576 maxwells. Finally, by applying equation 5, with a coil voltage of 800 V, the equation is:

$$800 = \sqrt{2}\pi(180)\, N_C\, (3485576)\, 10^{-8}$$

and solving for N_C the result is N_C = 28.7 turns. Rounding off, the result is 29 turns.

For temperatures below Curie, since H, μ, and Q are interrelated, it is necessary to assume a value for H, find the corresponding values for μ and Q and then substitute them into equation 10. If the equation is not satisfied, other values of H are tried until the equation is satisfied. In this case, a value of H = 2850 oersteds was found. Applying this to equation 4 results in a magnitude of flux equal to 3,290,051 maxwells and, using equation 5, the number of turns is found to be 30. By using the number of turns calculated for temperatures above Curie, viz., 29, it can be seen from equation 5 that to produce the same flux, below Curie, with less turns, less voltage will be needed. This only means that the coil voltage, to produce 900 KW, will be less below Curie than above. Thus, by using the number of turns calculated for above Curie, the 900 KW can be obtained throughout the heating cycle without requiring more than the system red-line voltage (800 V).

The current through the 17 inch diameter coil can be found from equation 7. Assuming 900 KW, the result is:

I = 5,181A (above Curie)

I = 3,794A (below Curie)

These are the values of current drawn by the coil when 900 KW is being delivered to the coil with 29 turns. The change in permeability of the steel as it goes above Curie temperature results in a change in impedance of the coil-workpiece combination. As a result, to deliver 900 KW to the coil above Curie temperature requires a greater voltage than is required below Curie. The resistance of the coil is, from equation 11,

$$R_c = \frac{(1.15)\ (1.73 \times 10^{-6})\ (136)\ (29)^2}{(53.34)\ \ (.494)} = .0086250\Omega$$

The power lost in heating the coil copper is then given as:

(above Curie) $P = I^2R = (5181)^2\ (.008625) = 232$ KW

(below Curie) $P = (3794)^2\ (.008625) = 124$ KW

Allowing for loss in the power line to the coil, the power into the coil would be:

900 KW - 12 KW = 888 KW (above Curie)

900 KW - 6.6 KW = 893 KW (below Curie)

The efficiency of the coil is:

$$\frac{888-232}{888} = .74 \text{ or } 74\% \text{ (above Curie)}$$

$$\frac{893-124}{893} = .86 \text{ or } 86\% \text{ (below Curie)}$$

The volt-amperes (VA) consumed by the coil are:

$$VA = 800(5181) = 4144800 \text{ (above Curie)}$$

$$VA = 755(3794) = 2864470 \text{ (below Curie)}$$

The power factor (PF) is:

$$PF = \frac{888 \text{ KW}}{4145 \text{ KVA}} = .2142 \text{ (above Curie)}$$

$$PF = \frac{893}{2864 \text{ KVA}} = .312 \text{ (below Curie)}$$

The values for power factor and efficiency change continuously throughout the heating. Thus, the values calculated here actually apply only at two specific points in time. They do, however, give general values that can be used for calculations above and below the Curie temperature and do give useful and sufficiently accurate results for calculating the number of coil turns required.

HEATING CYCLE:

Temperature profiles of a 13 inch outside diameter, 4.5 inch inside diameter preform and a 17.5 inch outside diameter, 6.75 inch inside diameter preform were obtained by putting thermocouples at various depths and positions. The heating tests were conducted by

Cheston personnel as part of the acceptance test for the induction system. Tables I and II show results of one heating test for each of the two preforms. Sixteen thermocouples were used in each preform. Tables I and II show results from only two thermocouples since they show readings on the inside and outside surface of the preform.

To test the accuracy of the equation given in Part I, equation 16 may be used to calculate the power density, P_o. Thus, for the 13 inch preform test run:

$$P_o = \frac{(7.832)(.177)(10.795)(1066)}{2(1920)} = 4.15 \text{ cal/sec-cm}^2$$

If this value for P_o is put into equation 15, the result is:

$$T_s\text{-}T_c = \frac{(4.15)(10.795)(.8)(1)}{2(.118)} = 152°\text{C or } 273°\text{F}$$

This compares to a measured difference of 243°F. Applying equation 17 the result is:

$$t_2 = \frac{.154(7.832)(.177)(10.795)^2}{(.118)} = 211 \text{ sec or } 3.5 \text{ min}$$

This compares to a measured time of about four minutes.

Similarly, for the 17.5 inch preform, the values are:

$$P_o = \frac{(7.832)(.177)(13.65)(1093)}{2(3180)} = 3.25 \text{ cal/sec-cm}^2$$

$$T_s\text{-}T_c = \frac{(3.25)(13.65)(.85)(.8)}{2(.118)} = 128°\text{C or } 280°\text{F}$$

$$T_2 = \frac{.154(7.832)(.177)(13.65)^2}{.118} = 337 \text{ sec or } 5.62 \text{ min}$$

These compare to measured values of 252°F and 6.5 minutes.

TABLE I

13 INCH PREFORM TEMPERATURES

(13 x 4.5 x 98 INCH PREFORM, 4337 STEEL, 17 INCH I.D. COIL)

TIME (min.)	POWER (KW)	TEMPERATURE (inside °F)	TEMPERATURE (outside °F)
5	900	228	702
10	900	577	1092
15	900	901	1427
20	900	1155	1591
25	900	1351	1763
30	600	1636	1999
32	power off	1830	2073

Power was 900 KW for 28 minutes and 600 KW for 4 minutes, then power was shut off.

TABLE II

17.5 INCH PREFORM TEMPERATURES

(17.5 x 6.75 x 75 INCH PREFORM, 4337 STEEL, 22 INCH I.D. COIL)

TIME (min.)	POWER (KW)	TEMPERATURE (inside °F)	TEMPERATURE (outside °F)
5	865	173	762
10	865	410	1073
15	865	652	1259
20	865	863	1440
25	865	1038	1592
30	865	1187	1752
35	600	1307	1803
40	600	1379	1905
45	600	1590	2021
50	600	1758	2085
53	power off	1848	2100

Power was 865 KW for 32 minutes and 600 KW for 21 minutes, then power was shut off.

The time to heat the preform can be calculated as outlined in Part I by applying equation 14. For the 13 inch preform the average power during the test run was 865 KW. Using an average efficiency of 77% (the efficiencies above and below Curie were calculated earlier as 74 and 86 percent; figuring 60% of the heat time above Curie and a 2% power line loss, the average efficiency is 77%), an average radiation loss of 58 KW, (the radiation power may be found from the equation

$$P = (5.453 \times 10^{-16})\ (A)\ (e)\ (T+459.67)^4$$

where T is temperature in degrees Fahrenheit, A is surface area in cm^2 and e is emissivity), and a value for the energy to raise the preform (3240 lbs of steel) to 2000°F, of 308 KWH (from the equation: KWH = $[.0000487(T)-.00216]\ \lfloor \text{Weight (lbs)} \rfloor$ with T in °F and T greater than 1500°F), the result is:

$$\text{Time} = \frac{308}{865(.77)-58} = .507 \text{ hour} \quad \text{or } 30.4 \text{ minutes}$$

compared to the actual time of 32 minutes. For the 17.5 inch preform, the results are:

$$\text{Time} = \frac{413 \text{ KWH}}{(760 \text{ KW})(.75)-79 \text{ KW}} = .84 \text{ hr.} \quad \text{or } 50.5 \text{ minutes}$$

compared to the actual time of 53 minutes.

Of course the specific heat, thermal conductivity and coil efficiency are changing continuously with temperature. Thus, the calculation procedure outlined here is quite crude in its approach. But it can be seen that the results calculated agree quite well with the measured values. The procedure can be used as a first approximation to the heating time and temperature difference and the process can be refined further by actual heating tests.

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